



Modeling and Simulation of MEMS Microthrusters

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June 21-25, 2004

Istanbul, Turkey

**AFOSR/EOARD Symposium on Energy
Conversion Fundamentals**

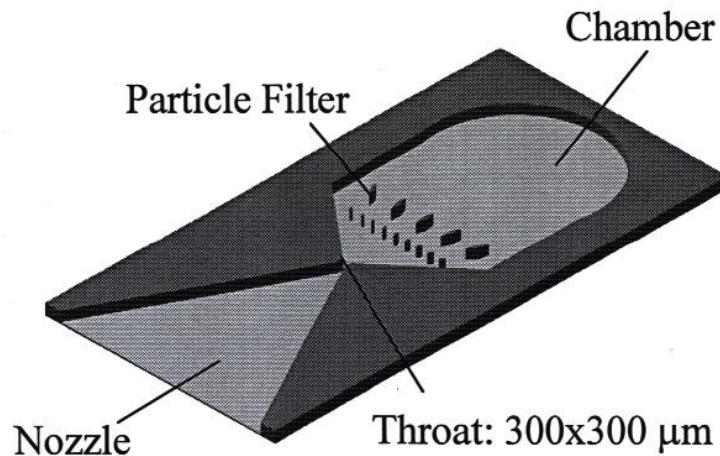
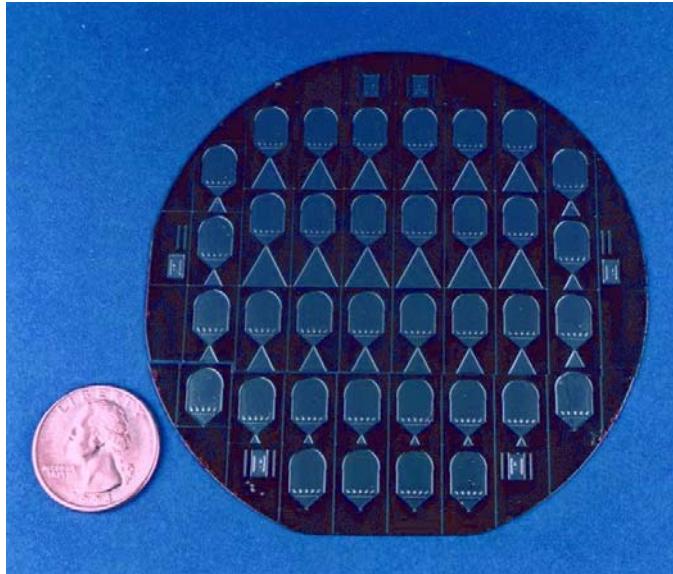
Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE 21 JUN 2004	2. REPORT TYPE N/A	3. DATES COVERED -
4. TITLE AND SUBTITLE Modeling and Simulation of MEMS Microthrusters		
5a. CONTRACT NUMBER		
5b. GRANT NUMBER		
5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)		
5d. PROJECT NUMBER		
5e. TASK NUMBER		
5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Aerospace Engineering Penn State University		
8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		
10. SPONSOR/MONITOR'S ACRONYM(S)		
11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited		
13. SUPPLEMENTARY NOTES See also ADM001793, International Symposium on Energy Conversion Fundamentals Held in Istanbul, Turkey on 21-25 June 2005., The original document contains color images.		
14. ABSTRACT		
15. SUBJECT TERMS		
16. SECURITY CLASSIFICATION OF:		
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified
17. LIMITATION OF ABSTRACT UU		
18. NUMBER OF PAGES 25		
19a. NAME OF RESPONSIBLE PERSON		

MEMS-Based Propulsion



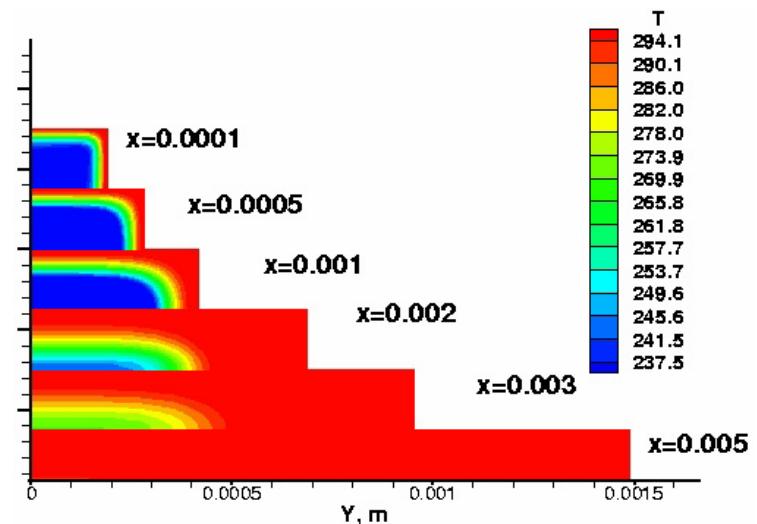
- To enable formation flying concept new propulsion systems are needed that can deliver precise impulse bits under strict mass, size and power limitations.
- Various MEMS-based propulsion systems are considered for such missions: cold and heated gas, bipropellant, catalytic and solid decomposition thrusters.

Physics of Micro-nozzle Flows

- Due to the reduced physical size, frictional surface effects can dominate the gas flow in microthrusters.

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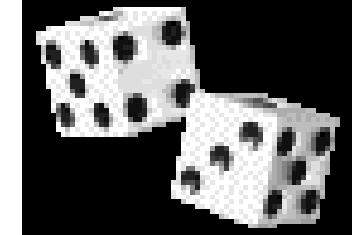
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Comparison of boundary layers for traditional axisymmetric vs MEMS flows.

Development of 3D boundary layer in a cold gas flow.

- In addition, wall temperature, heat transfer, and heat fluxes are major controlling factors for microthruster performance, yet it is often an unknown in the system design.



The DSMC Method

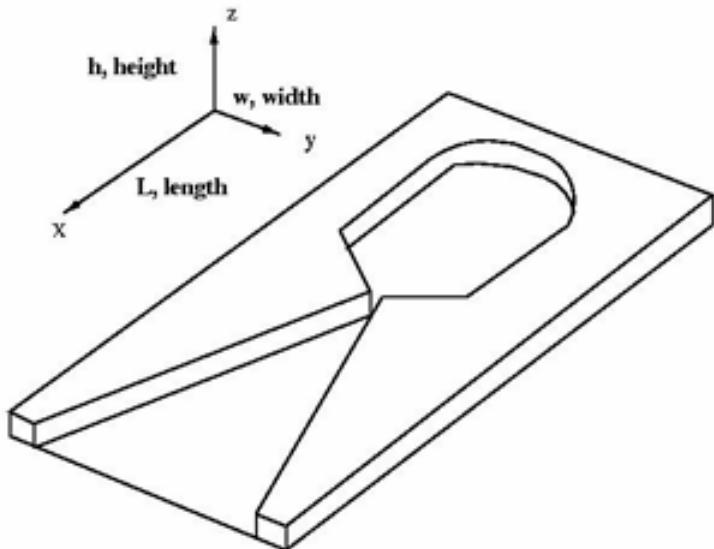
- A simulation tool for modeling chemically reacting flows in *rarefied/transitional* environments.
- $Kn = \mathcal{M}_{ref}$, λ = mean free path, l_{ref} = reference length
 - Continuum: Navier-Stokes, $Kn \leq \sim 0.001$
 - Transitional: DSMC, $Kn \geq \sim 0.01$
- Developed by G. Bird to obtain a solution of the Boltzmann equation,
 - follow the motion of many virtual molecules on a grid, for a series of time steps,
 - calculate particle collisions using Monte Carlo techniques.
 - model gas-surface interactions,
 - using conservation relationships, obtain changes in internal energies and velocities of the components.
- Flows around spacecraft and micro-propulsion devices can be modeled by DSMC because they have similar Kn .



Outline of Talk

- **Cold gas thrusters - effects of**
 - geometry: 3-D , 2-D, axisymmetric,
 - gas surface model,
 - performance.
- **Higher temperature gas thrusters - effects of,**
 - flowfield dependence on T_o, p_o
 - gas- surface interaction,
 - stagnation conditions and internal energy on performance.
- **High-temperature gas thrusters with variable T_{wall} ,**
 - coupled DSMC/FEM method,
 - variable material cooling conditions,
 - time-dependent calculations of thrust and material characteristics.

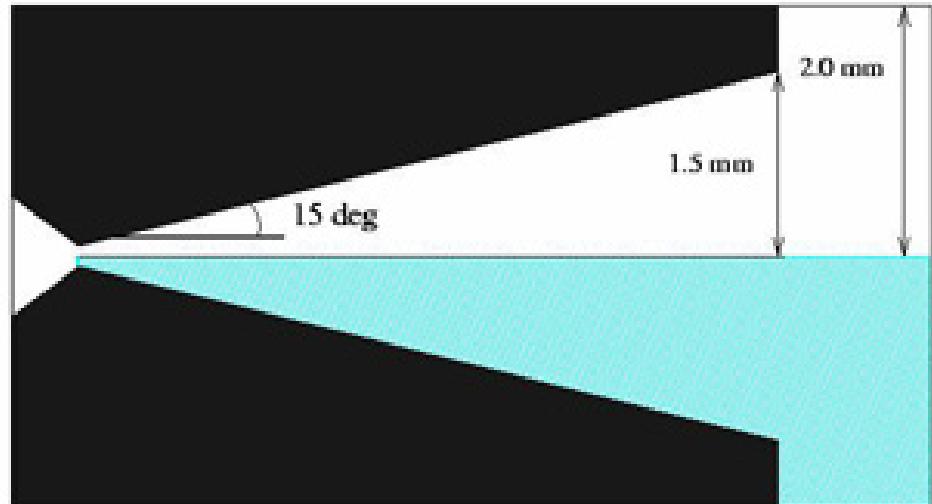
Cold Gas Thrusters - Geometry



- 3D flat nozzle

- XY plane expansion angle $\alpha = 15^\circ$
- throat width $w = 300 \mu\text{m}$
- throat height $h = 300 \mu\text{m}$
- Area ratio $A_e/A^* = 10$

- 2D nozzle, neglect surfaces in x-y plane, for $z=0, h$



- Axisymmetric

- expansion angle $\alpha = 15^\circ$
- throat radius $R_t = 150 \mu\text{m}$
- Area ratio $A_e/A^* = 100$

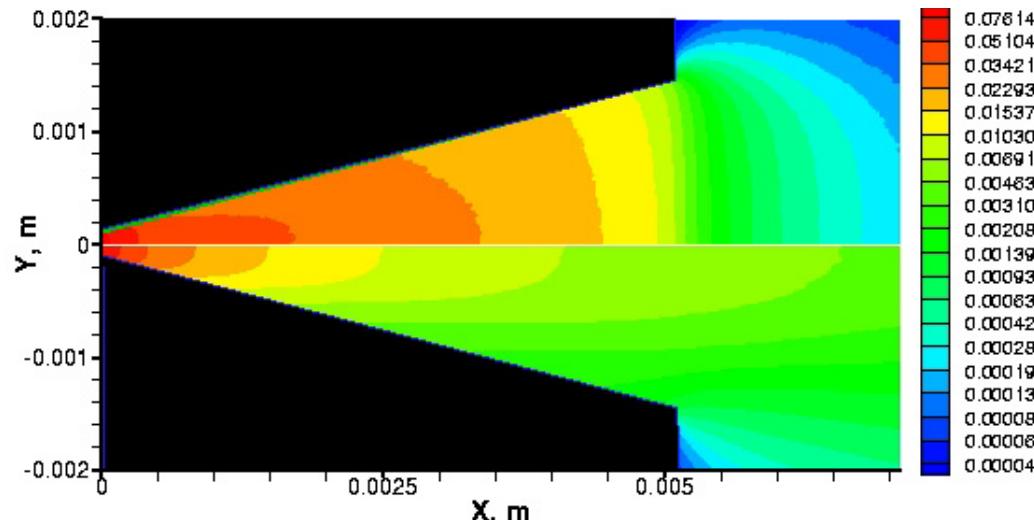


Cold Gas Thruster - Conditions

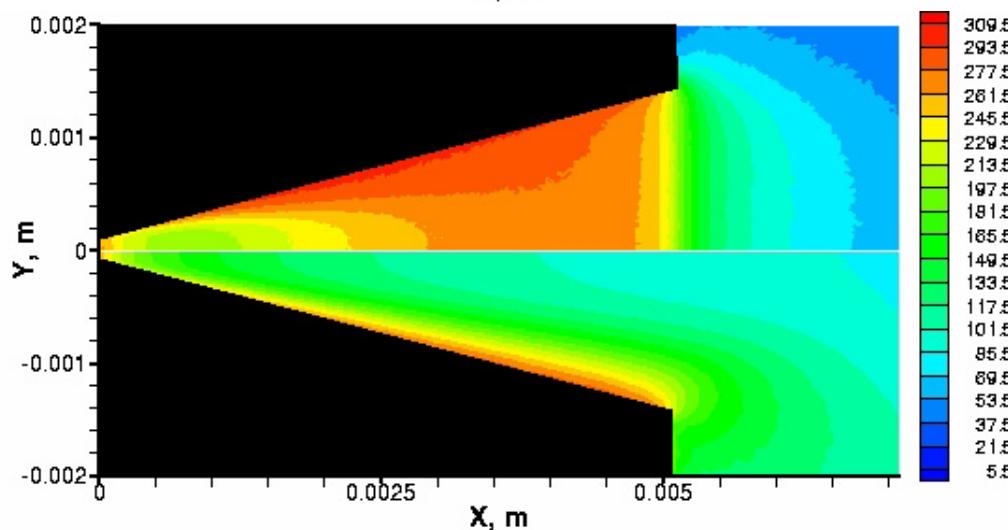
- Test gas N_2
- Stagnation temperature and pressure $T_c = 300 \text{ K}$, $P_c = 10 \text{ kPa}$
- Critical temperature and pressure $T_t = 250 \text{ K}$, $P_t = 5.2 \text{ kPa}$
- Wall temperature $T_w = 300 \text{ K}$
- Knudsen number (mean free path/char length) $Kn = 5 \times 10^{-3}$
- Reynolds number (mom/viscous ratio) $Re = 200$

Cold Gas - Effect of Geometry

Top - 3-D, Bottom - 2-D



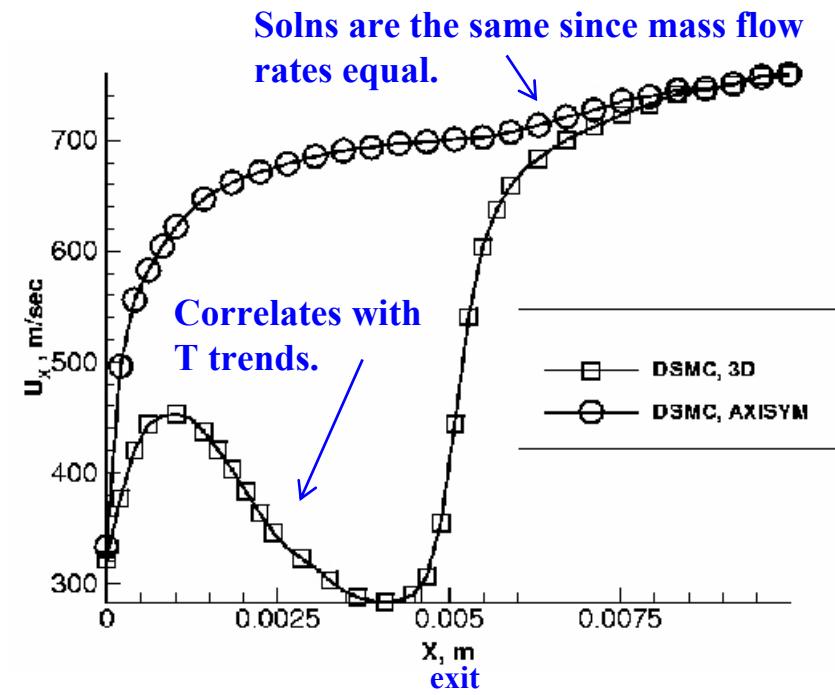
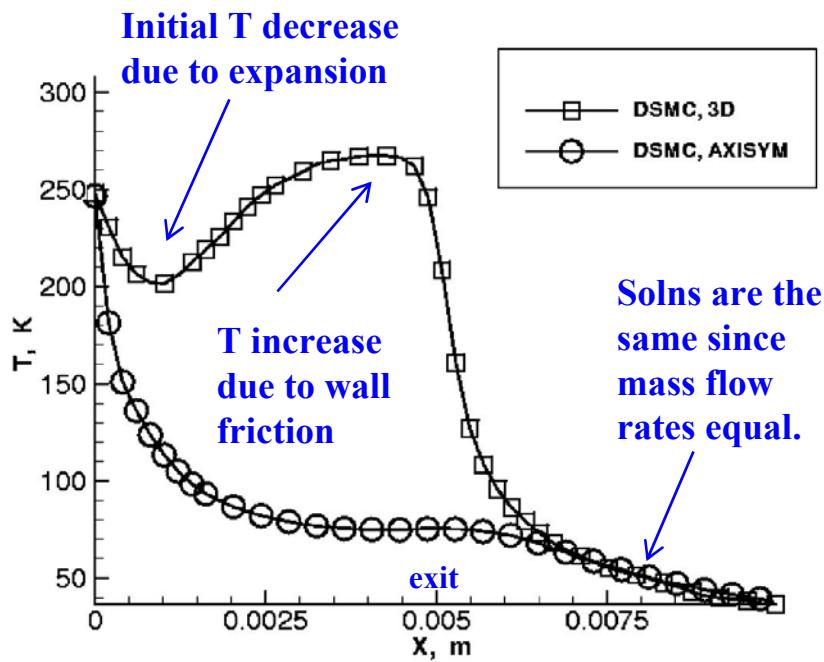
- Density, kg/m^3
- Greater flow expansion in 2-D case.



- T, K
- More heat transfer to the wall in the 3-D case.

Cold Gas - Effect of Geometry

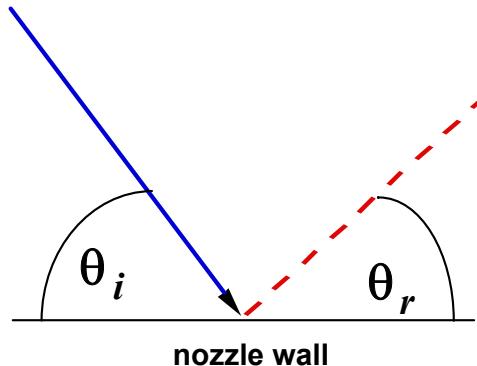
3-D vs. Axisymmetric



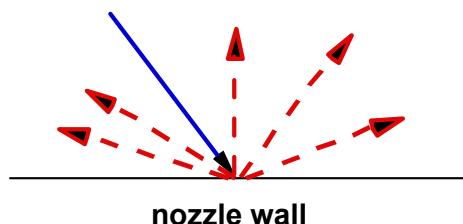
- 3-D vs axisymmetric shows that the degree of wall surface area is important.
- For supersonic nozzle flow into a vacuum, U_x should be a maximum at the exit.
- Instead, extremum U_x is located upstream due to subsonic region at the walls.

Kinetic, DSMC Gas-Surface Wall Models in Micro-nozzle Flows

Specular reflection



Diffuse reflection



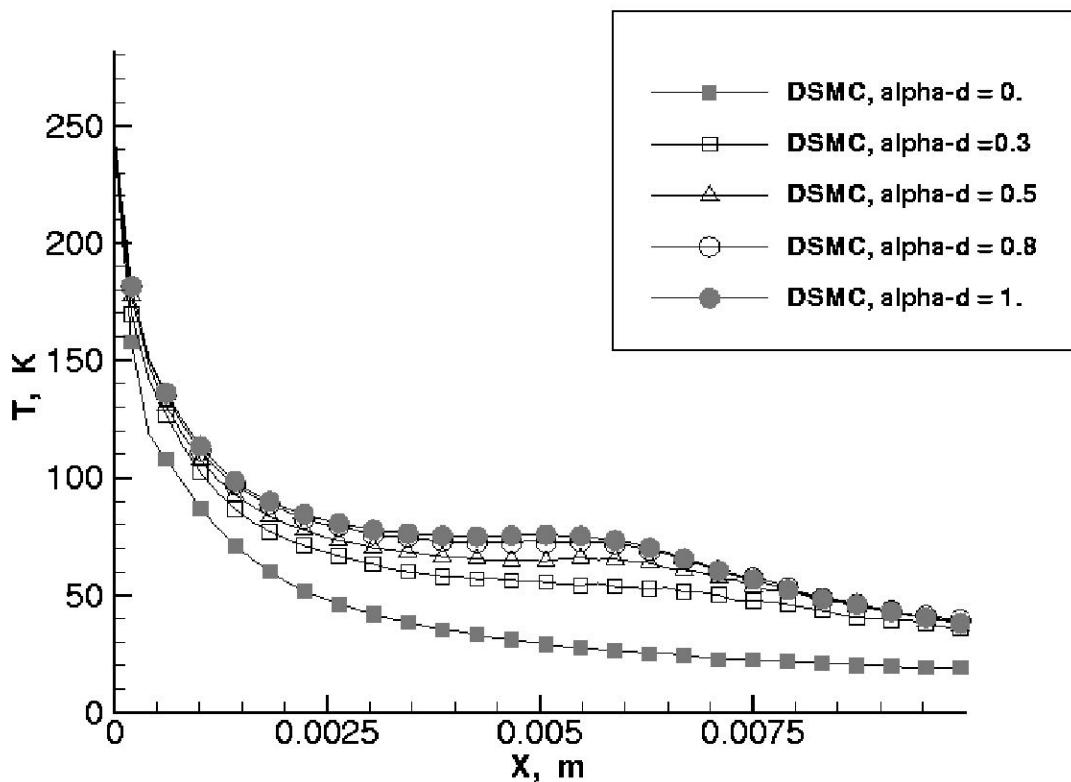
incident gas molecule
reflected gas molecule

- Two types of gas-surface interactions

- Specular - incident and reflected tangential momentum are the same,
- Diffuse - all reflected directions are equally probable, wall acts like an emitting source of particles at T_{wall} ,

- Interaction is specified by with accommodation coefficients for
 - Normal momentum, tangential momentum, and energy (heat transfer)
 - Values between 0,1 and closer to 1 for spacecraft materials.
- Continuum methods are partially corrected with wall slip-jump boundary conditions.
- Accommodation ~ 1 generates large, viscous boundary layers.

Cold Gas Thrusters - Effect of Gas-surface model

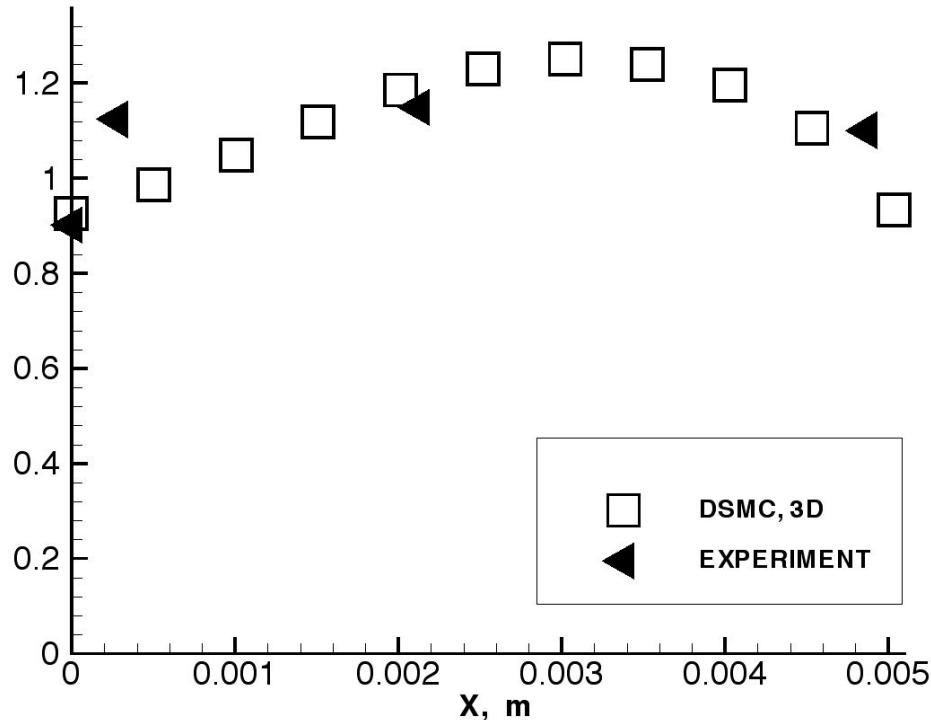


Translational T profiles along the nozzle axis for different α_d in an axisymmetric micronozzle.

- Definition of tangential momentum accommodation coefficient,

$$\alpha_d = (P_{\tau i} - P_{\tau r}) / P_{\tau i}$$
- Experiments show that $\alpha_d = 0.8$ for silicon.
- 3-D calculations showed only 1% difference for $\alpha_d = 0.8$ and 1.

Cold Gas Thrusters - Performance

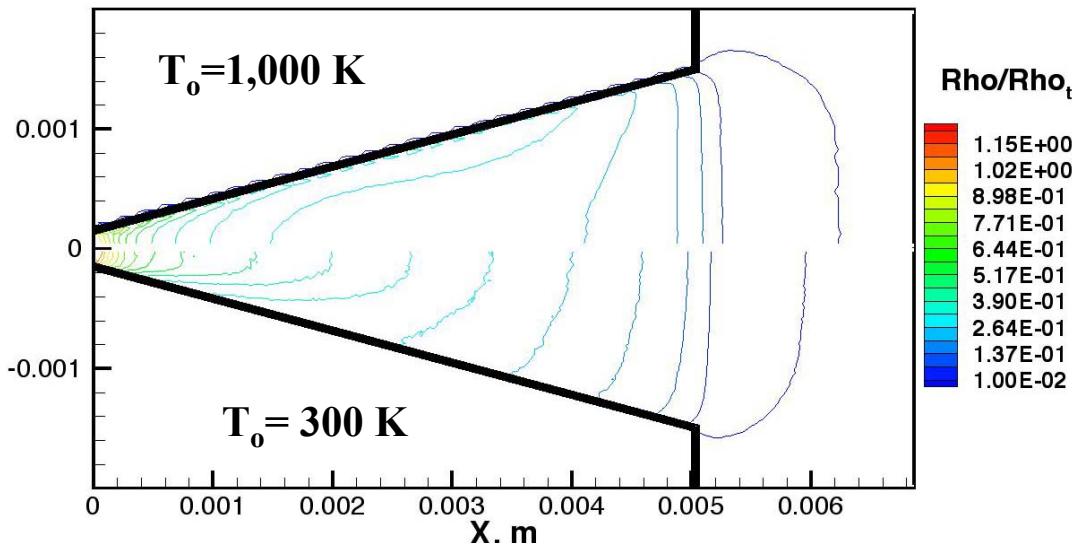


- Comparison of 3-D calculations with data show good agreement.
- 2-D assumption is poor and over predicts thrust levels of geometry.
- Wall effects in 3-D case reduce thrust (20%) and specific impulse cf to 2-D.

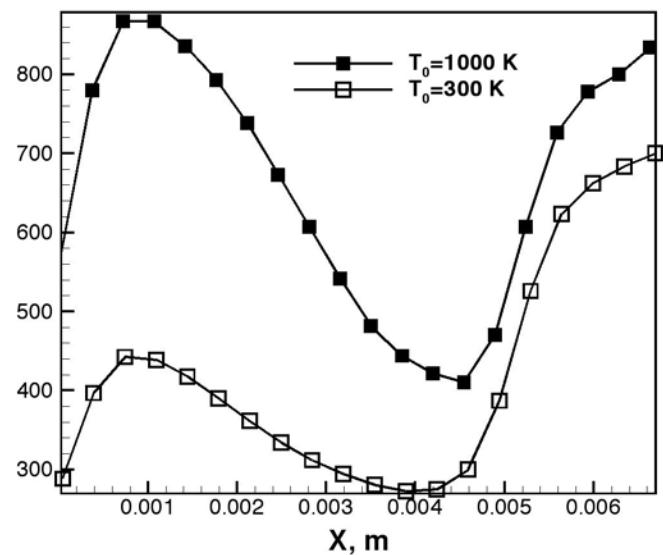
Higher-Temperature Thruster Flows

Full wall accommodation, $Re_t \sim 200$, $T_w = 300$ K, 3-D nozzle

Normalized density

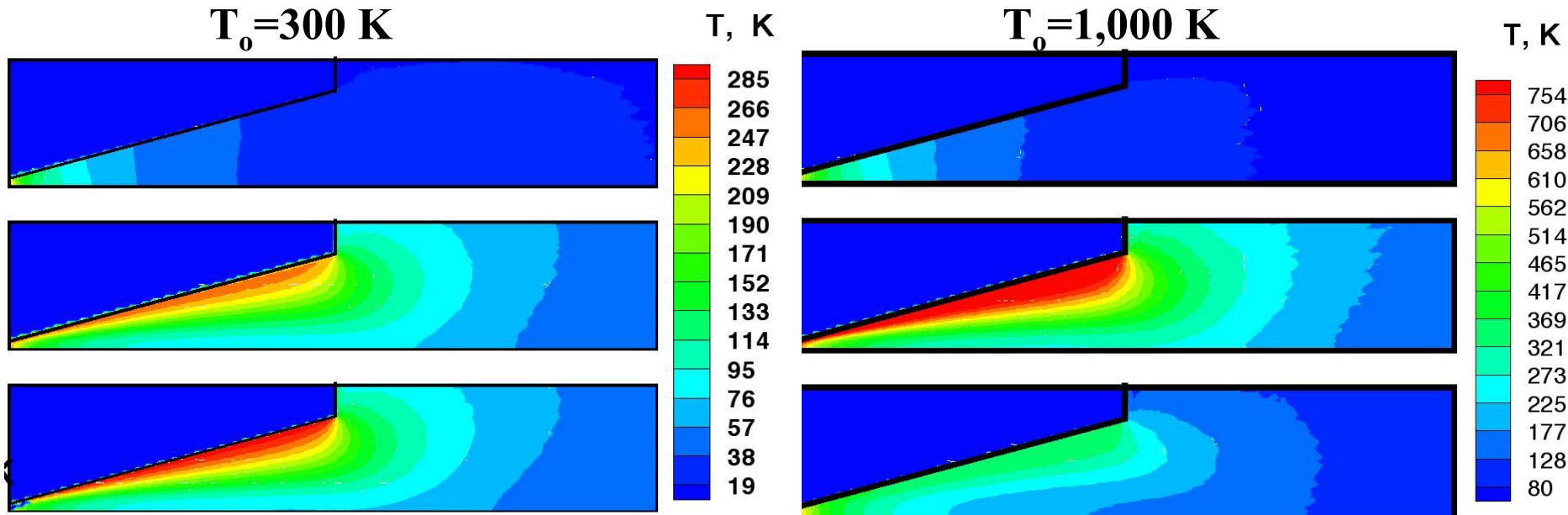


U_x along centerline



- Flows at both temperatures are dominated by surface interactions, but structure is different.
- $I_{sp} = 56.6$ and 61.8 for $T_o = 300, 1000$ K, respectively.
- Increase in I_{sp} << than for comparable axisymmetric case due to larger surface-area-volume ratio.

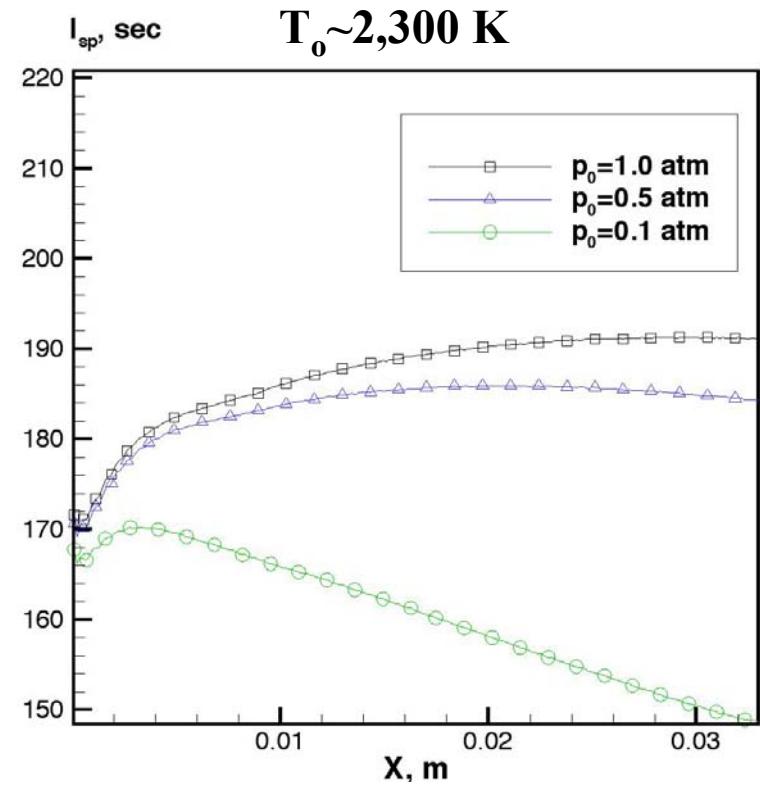
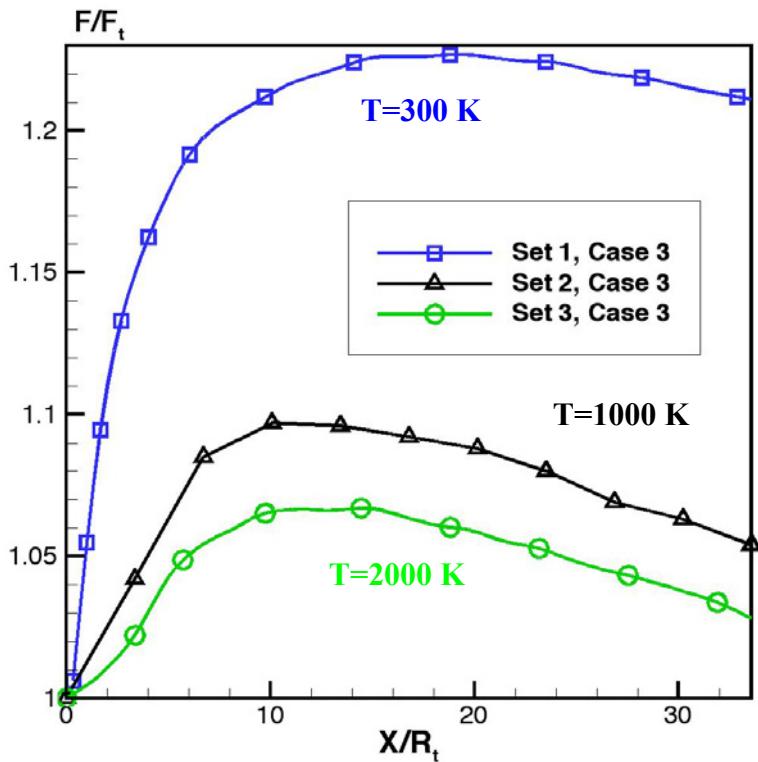
Comparison of Flows for Different Gas - Surface Models and T_0



1. “Specular” = ideally smooth, no momentum or energy transfer (TOP),
2. “Diffuse, adiabatic” = av tangential momentum of reflected molecules = 0, no energy transfer with wall (MIDDLE).
3. “Diffuse, $T_w=300$ ” = both momentum and energy transfer occurs with wall (BOTTOM).

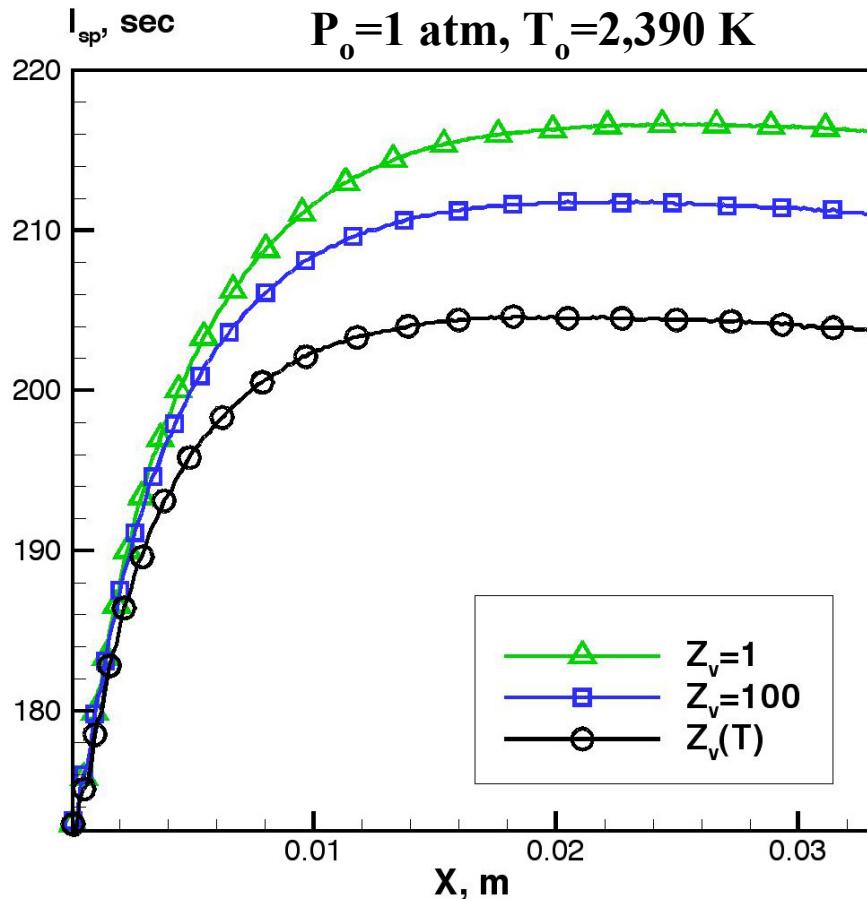
Effect of T_o and P_o on Performance

Axisymmetric nozzle, Diffuse wall, $T_w=300$



- For high T_o , a shorter nozzle would give better performance at lower Re .
- Need to optimize geometry of high temperature nozzles.
- For lower pressures, the peak value of I_{sp} is closer to the nozzle throat.

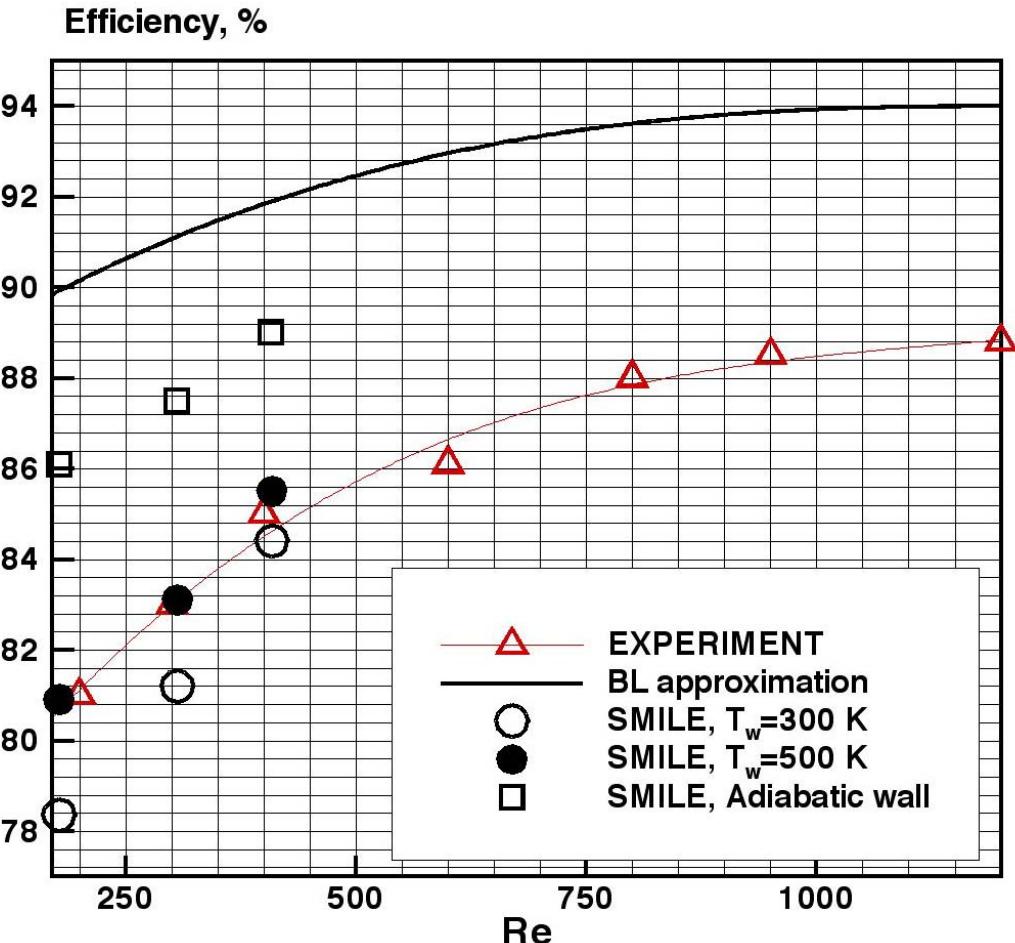
Effect of Internal Energy* on Performance



- Axisymmetric nozzle, hydrogen air mixture $\Rightarrow 66.1\% \text{ N}_2$, 32.4% H_2O , and 1.5% H_2
- High T polyatomic gas, VT becomes important.
- Represent VT by Z_v relaxation numbers in Larsen-Borgnakke model:
 1. $10^4 < Z_v(T) < 10^6$
 2. Constant $Z_v = 1$ and 100.
- Faster VT relaxation increases nozzle performance.

*For cold gas thrusters, TR relaxation is the dominant internal energy transfer mechanism.

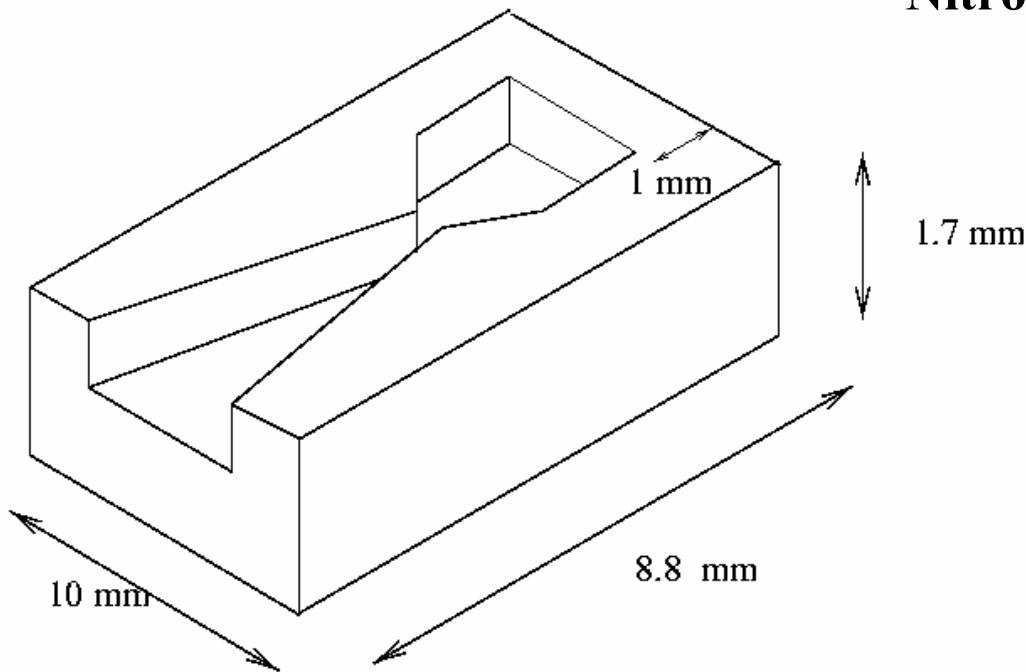
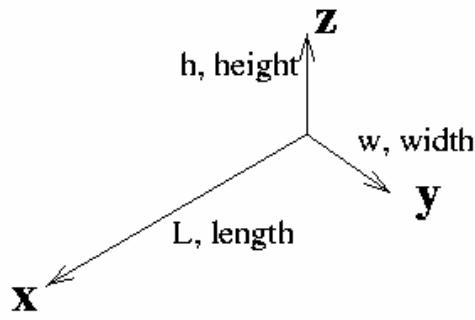
Comparison of Calculated and Measured Efficiencies for Axisymmetric Nozzles



- Experimental data did not specify T_w .
- Good agreement between measurements and modeling for $T_w=500$ K and complete accommodation.
- I_{sp} sensitive to wall conditions.
- *Need a predictive capability to determine both material and gas properties for micropropulsion devices.*

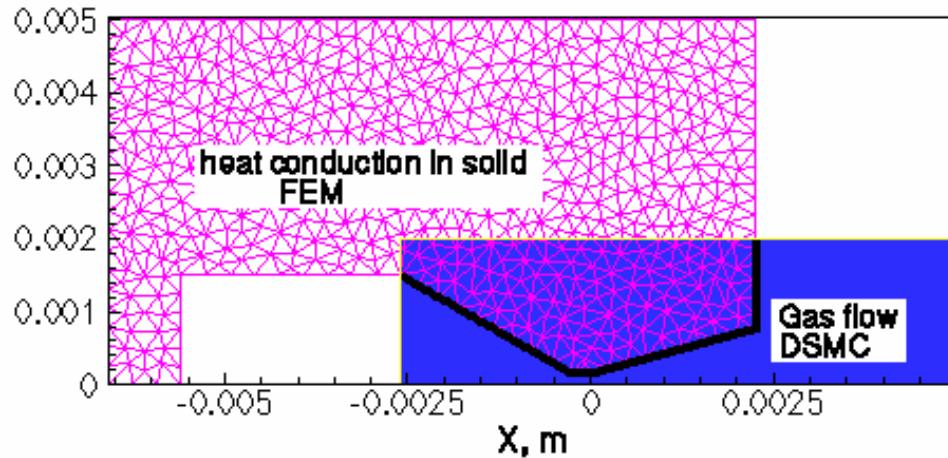
Geometry and Flow Conditions

Schematic of NASA-Glen Microthruster



- **30 deg converging part**
- **15 deg diverging part**
- **Exit to throat area ratio of 5**
- **Throat: $300\mu\text{m} \times 600 \mu\text{m}$**
- **Nitrogen flow:**
 - $P_0 = 0.1$ and 0.5 atm,
 - $T_0 = 2000$ K,
 - $Re = 35$ and 175 , respectively.

Coupled Thermal and Gas Dynamic Computational Approach



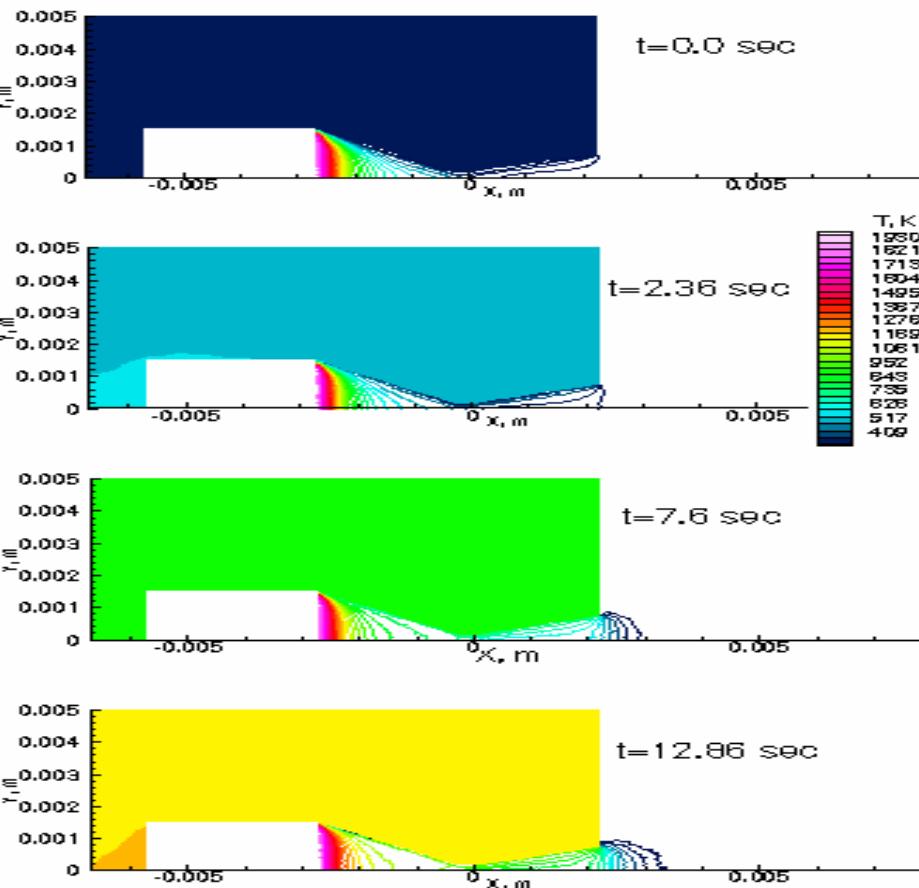
Computational domain for 2D calculations

- Based on the solution of the heat transfer problem using finite element method coupled to the DSMC gas flow solution.
- Coupling between material thermal response and flow by using DSMC heat fluxes as the boundary conditions for the heat conduction problem.
- The wall temperature calculated in the heat transfer simulations is, in turn, applied as a boundary condition for DSMC calculations.

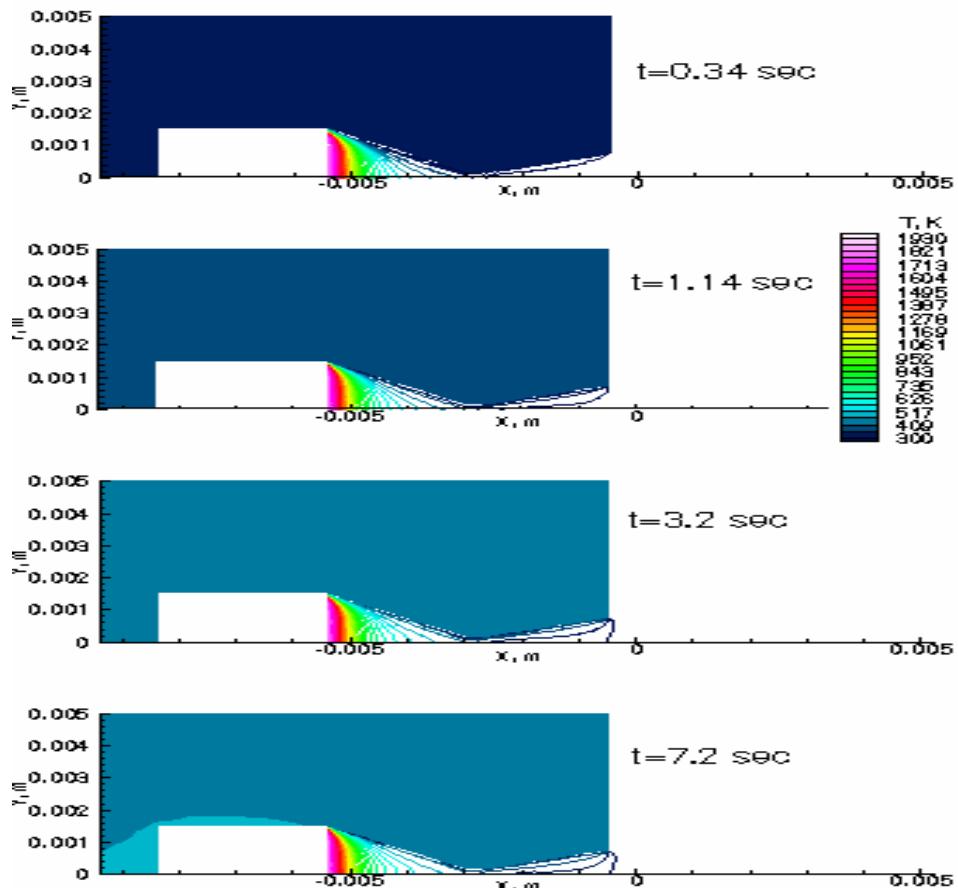
Material thermal response: 3D

Time variation of the temperature fields for 0.1 atm

Thermally Insulated

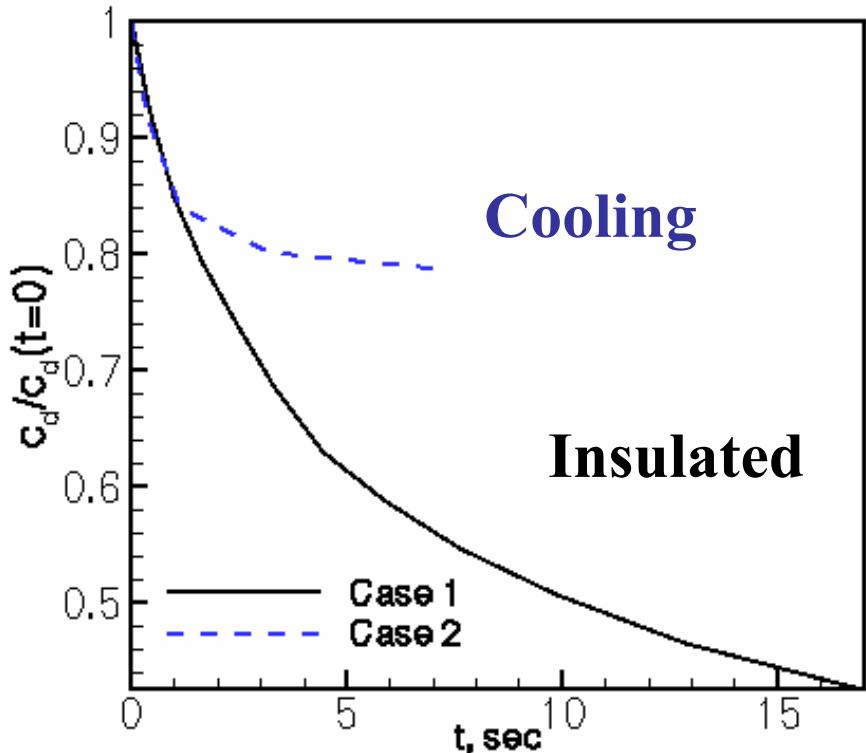
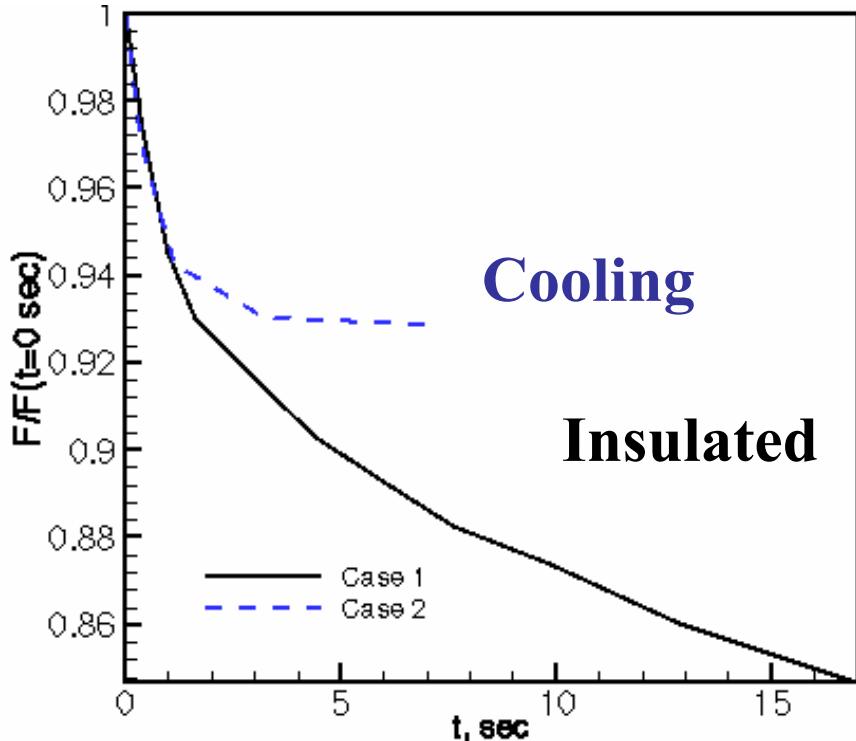


Active Cooling



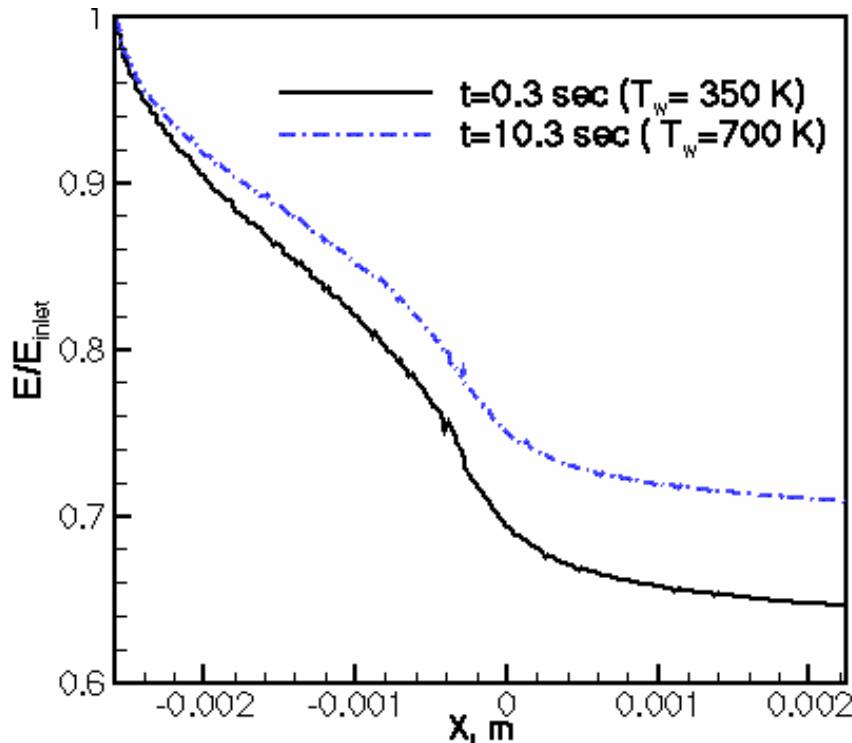
Micronozzle performance

$h=600 \mu\text{m}$, $p_0=0.1 \text{ atm}$, insulated vs cooling



- Final thrust value, F , are 15% and 6% lower than the initial ones for Case 1 and 2, respectively.
- The mass flow degradation is as much as 55% in Case 1.
- Coeff. of mass discharge, C_d , decreases more rapidly than F .

Where does the energy go?



- 2-D, $p_0 = 0.5 \text{ atm}$, cooling, (AIAA 03-0673).
- Cooling allows heat transfer losses.
- As material heats up, less gas energy is transferred to the wall.
- As material heats up, reduction in thrust will slow down.

Ratio of gas energy to value at inlet along the nozzle axis.

Conclusions

- Material thermal response is similar to 2D, but gas flow structure is significantly different due to the side-wall boundary layer.
- For thermal cooling, the steady-state material temperature is 450 K (same as in 2D).
- Higher Re flow results in larger surface heat fluxes and, thus, shorter operational times. However, heat fluxes do not vary proportionally with Re.
- Cooling applied to the outer surface can sustain the material temperature below melting. Cooling results in improved thrust and mass discharge performance.
- The large temporal variation of the thrust, and especially mass discharge coefficient means that the coupling between the gas and material must be taken into account in micropropulsion design.



Related Publications

1. Alexeenko. A., Fedesov, D., Levin, D., Gimelshein, S., and Collins, R., “Transient Heat Transfer and Gas Flow in a MEMS-based Thruster,” submitted to the *IEEE J. of MEMS*, April 17, 2003.
2. Alexeenko, A. A., D. A. Fedosov, D. A. Levin, S. F. Gimelshein, R. J. Collins, “Performance Analysis of Microthrusters Based on Coupled Thermal-Fluid Modeling and Simulation”, Submitted to the *Journal of Power and Propulsion*, Sept., 21, 2003.
3. Lempert, W., M. Boehm, N. Jiang, S. Gimelshein, and D. Levin, “Comparison of molecular tagging velocimetry data and direct simulation Monte Carlo simulations in supersonic micro jet flows,” *Experiments in Fluids*, 2003 , Vol. 34, pp. 403-411.
4. Alexeenko, A.A., D. Levin, S. Gimelshein, R. Collins, G. Markelov, “Numerical Simulation of High-Temperature Gas Flows in a Millimeter-Scale Thruster,” *Journal of Thermophysics and Heat Transfer*, January-March, 2002, Vol. 16, No. 1 pp. 10-16.
5. Alexeenko, A.A., D. Levin, S. Gimelshein, R. Collins, and B. Reed, “Numerical Modeling of Axisymmetric and Three-Dimensional Flows in MEMS Nozzles,” *AIAA Journal*, Vol. 40, Number 5, May 2002, pp .897-904.



Acknowledgements

This research was supported by the National Aeronautics and Space Administration, John H. Glenn Research Center under Grant No. NAG3-2590 technically monitored by Mr. Brian D. Reed.

We would also like to thank Dr. Clifton Phillips of SPAWARSYSCEN who provided us with computer time on DoD Maui High Performance Computing Center.